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Influence of Long-Term Mine Activity on Hydraulic Relations between Separate Hydrogeological Units—New Aspects of Regional Water Circulation Assessment

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Abstract: In the course of the documentation works aimed at updating exploitable resources of the groundwater intake, an unexpected change in hydrodynamic field arrangement was observed in a fragment of the area. In relation to the observations made so far, lasting several decades, the groundwater table switched its slope, indicating the flow in the opposite direction than originally. Initially, in the range of the surveyed hydrogeological structure, no object was identified whose draining character could cause such an effect. No significant groundwater extraction or drainage points were documented within a radius of several kilometers. It was only the extended scope of spatial analysis that made it possible to identify the probable cause of a local change in the water table position as a mining pit located in the neighboring hydrogeological structure. The two adjacent hydrogeological structures treated separately so far revealed an experimentally confirmed hydraulic connection. An in-depth analysis of the problem showed the necessity of modifying the existing model of the structure in order to map the observed interactions. An additional simulation module of General-Head Boundary type was applied. The quantity of lateral groundwater exchange between two hydrogeological structures was estimated using mathematical modeling at 3.4 thousand m^3/d (reconstructed current state, after model calibration). Further work should aim at treating reservoirs as hydraulically connected after exceeding limiting parameters.

Keywords: groundwater; mining drainage; hydraulic connections; numerical model; finite differences method; hydrogeological prognosis; Kielce

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1. Introduction

Opencast mining of raw materials on an industrial scale is carried out in excavations with a significant horizontal spread (areas of a dozen or several hundred hectares) and a significant depth (even several dozen meters). In most cases, under typical hydrogeological conditions, it means the necessity to pump significant amounts of water flowing into the excavation, usually in the form of underground inflow. With unchanging mining conditions, the inflows, considered as averaged over a longer period, are usually relatively stable. The requirements of safe mining exploitation force drainage of the excavation in most cases in a continuous manner with maintaining the appropriate reserve capacity of the pumping system. This is an important issue, because although the mining exploitation is carried out at a stable level (without changing the base of drainage), the actual amount of inflows may change in time, depending on the intensity of the precipitation. In the case of heavy rainfall, when the inflow changes are rapid, proper design and operation of the drainage system may be critical for the safety of mining works.

The intensity of inflows to mine workings depends on many factors, including its size (horizontal extent), depth of dewatering resulting from the deposit cutting, rock mass parameters, location of the workings in relation to rivers, surface reservoirs, flow barriers, as well as climatic conditions [1]. Depending on these factors, mine inflow volumes can vary significantly. Diverse examples of mine inflow characteristics can be found in the works of among others [2–5]. On the other hand, the impact of mining waste deposition sites on groundwater, which is most often of a multi-scale nature, is described, among others, by [6–8].

Long-term mining dewatering, conducted over a significant spatial extent, both horizontally and in-depth, may result in unexpected environmental effects. While within the limits of a particular hydro-structural unit the influence of mining dewatering on the hydrodynamic field is obvious (any major change will cause a reaction of the hydrodynamic field), such influence on the neighboring separate units can hardly be expected. However, such an assumption should not be taken as an axiom. Observations made by the authors indicate that in a given situation, the influence of significant drainage may be noticeable also in a neighboring unit. For this to happen, two major factors must occur: (1) stressing drainage should be significant (in terms of extent and amount of water discharged) and (2) the drainage process should last for a sufficiently long time. Under special circumstances, the effects of such an impact may be evident in the form of even a relatively small change, in an originally treated completely separate adjacent unit. The authors of the article encountered such a case while working on the update of the resources of a large groundwater intake located in central-southern Poland. Locally limited arrangement of the groundwater table, different from that previously observed, led to considerations of the necessity to change the view on the regional hydrogeological conditions of water circulation in two previously treated as separate hydrogeological units.

Considering this type of complex dependence in a purely analytical way has a qualitative value, resulting in the lack of quantitative characteristics of the problem. Helpful in such applications are methods of mathematical modeling of groundwater filtration processes, considered one of the most accurate research methods in hydrogeology for predicting the distribution of the hydrodynamic field, including differentiated stresses [9–12]. Numerous examples demonstrate the utility of the method in solving inflow issues underground [13–19] as well as in open-pit mining [20–26]. In practical applications related to groundwater filtration modeling taking into account mine drainage systems, both the finite difference method (based on simulators of MODFLOW family [27]) and the finite element method (FEFLOW program [28]) are used. Simulation calculations are carried out for steady-state conditions or transient conditions.

In the analyzed case, collected observations and conclusions drawn from them made it possible to prepare appropriate corrections in the assumptions of the updated hydrogeological numerical model of the aquifer, to include the impact from the outside of its boundaries, and as a result, to make the prognostic calculations more reliable.

2. Materials and Methods

2.1. Regional Environmental Characteristics

The study area is located in central-southern Poland, in the vicinity of Kielce city (Figure 1), with a population of almost 200,000 inhabitants (18th most populous city in the country). The water supply is entirely covered by groundwater intakes scattered around the periphery [29]. The conducted research, described in this article, was related to the updating of the water resources of the largest municipal intake.

Physiographically, the study region belongs to the Polish Uplands [30], remaining on the border of the Paleozoic Holy Cross Mountains and their younger, northwestern undulating margin. Low and rounded mountain ranges extend in a WNW–ESE direction. The highest peaks in the neighborhood reach absolute heights of 400 m above sea level, while the valleys and foothills are located about 100–150 m lower.

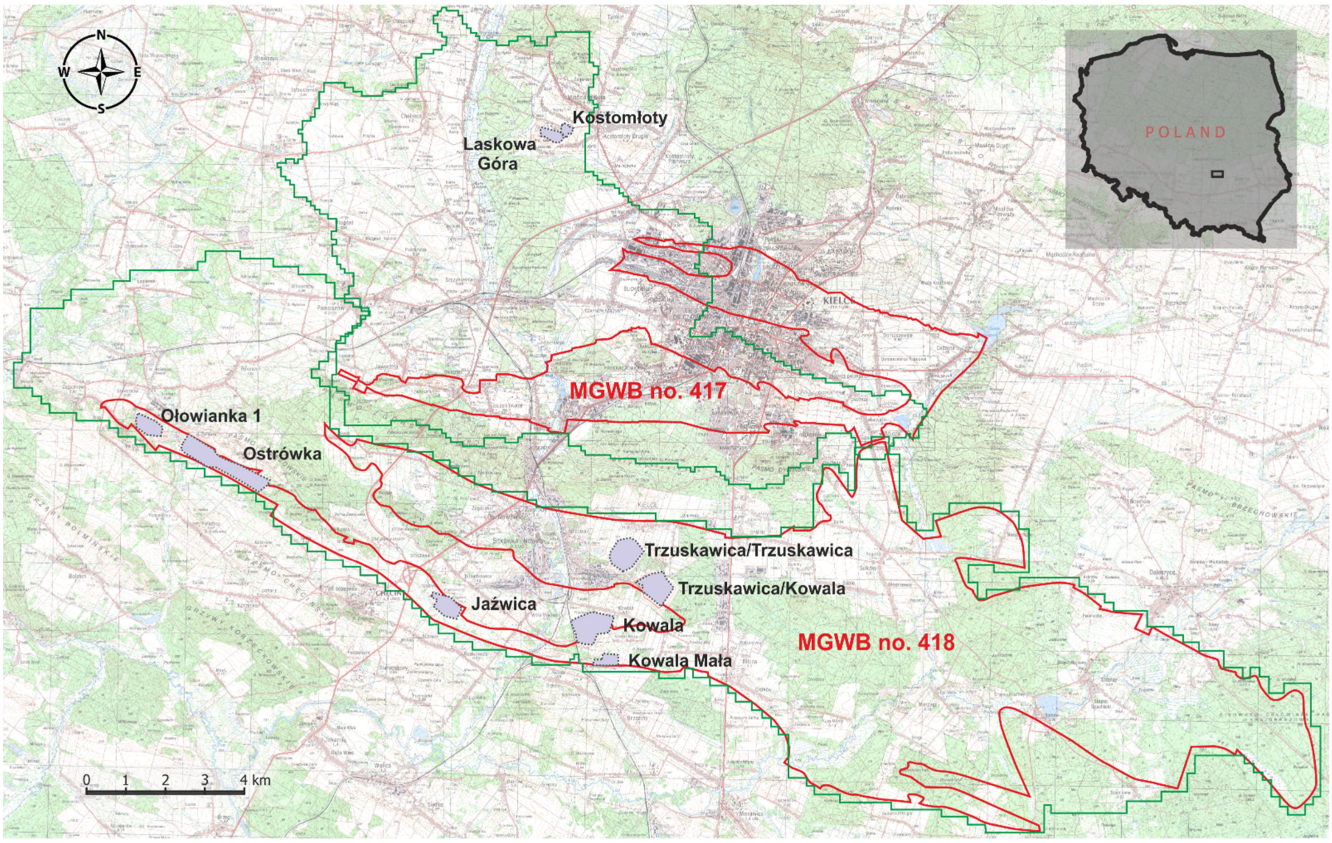

Figure 1. The spatial location of the MGWB (red lines) along with the boundaries of the numerical models used to date (green lines) and the location of mining areas (purple zones). A small map shows the location of the research area against the Polish borders.

The rivers flowing between the mountain ranges frequently cut through the edge parts of the margin with their breakthrough sections. Drainage mainly takes place from the north towards the south and further in the southwest direction, towards the vast valley of the main polish river—Vistula. The most important rivers are, starting from the west: Łososina (Wierna River), Bobrza together with its tributaries (Silnica and Sufraganiec), Lubrzanka and Bełnianka flowing into Czarna Nida and further to Nida—a direct tributary of Vistula River.

Geologically, the southeastern part of the area is made up of strongly eroded Holy Cross Mountains, formed during the Caledonian and Hercynian orogeny. The northwestern part, fringing the mountain ranges, was covered by sediments during the Permian–Mesozoic transgressions, which as a result of later processes, were slightly deformed to form large-radius folds. Marine sediments are present in the open to the western valleys of the Holy Cross Mountains, covering parts of the synclines with increasing to the west layer. The study area includes two adjacent synclines, the Kielce syncline (to the north) and the Gałęzice–Bolechowice–Borków syncline (to the south). Centers of the concave parts of the folds are filled with Devonian carbonate sediments up to 1000 m thick (Figure 2), to a much lesser extent covered with Carboniferous sediments (MGWB no. 418). Lithologically, the Middle Devonian dolomites dominate, with limestone and marl in the minority. Cores of the anticlines are made of formations of the Lower Palaeozoic age, mainly Cambrian. Lithologically, clay shales, siltstones and greywackes dominate. The sediments covering the northwest represent Permian and Triassic ages. Within cores of the Mesozoic age synclines, Upper Triassic sediments were documented. The central parts of the anticlines are formed by Lower Triassic formations. Lithologically, these are claystones, siltstones, calcareous sandstones and conglomerates, while in the upper part of the profile mainly limestones and marls. The prevailing part of the terrain surface is covered by a layer of Quaternary sediments, mainly of post-glacial origin. In the river valleys, fluvial and fluvioglacial deposits appear.

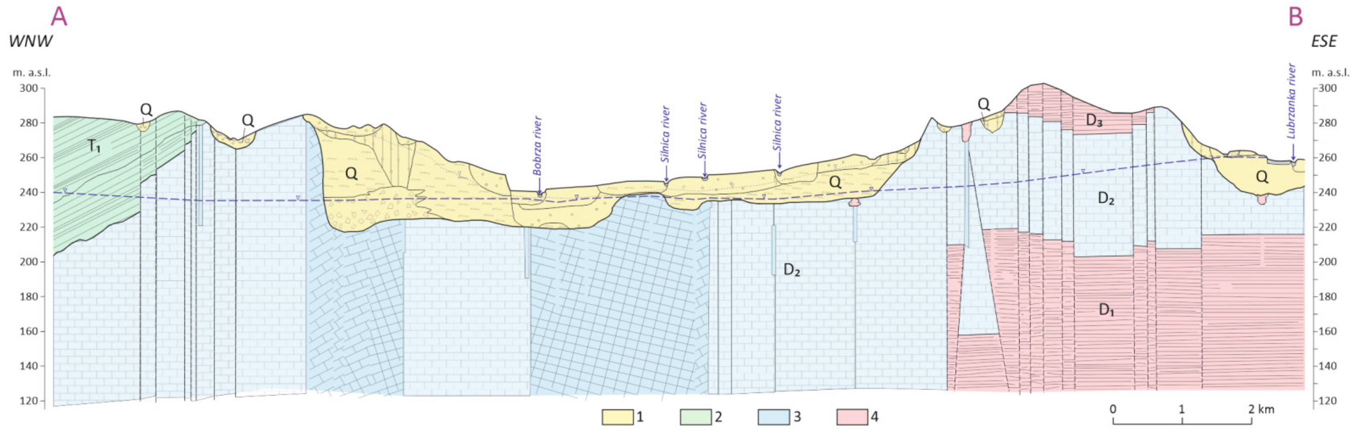

Figure 2. Geological cross-section of the modelled area of the MGWB No. 417 (according to [28]; the cross-section line is shown in Figure 5) 1—pore aquifers within Quaternary sediments (permeable and poorly permeable sediments), 2—fracture and fissure-pore aquifers, 3—karst-fissure reservoirs, 4—impermeable units.

Most water-bearing structures are Devonian syncline cores made of thick dolomites. These dolomites, as well as other carbonate formations, are subject to intensive mining exploitation. They form irregular, elongated structures of fissure and karst character. The carbonate formations that make up the aquifer are characterized by very variable permeability, from very good to poor. The hydraulic conductivity values range from 1.3×10^{-7} to 1.2×10^{-3} m/s [31–33]. The most water-rich fragments, forming so-called Major Groundwater Basins (MGWB), were separated within the boundaries of the formations. According to the national classification, a MGWB is a geological structure or its fragments with the highest water-bearing and storage capacity in the scale of hydrogeological regions. In the area under consideration, two such reservoirs have been distinguished: MGWB No. 417 Kielce in the north and MGWB No. 418 Gałęzice–Bolechowice–Borków in the south (Figure 1).

The older Paleozoic formations are generally classified as isolating. Carboniferous sediments have a similar status. Permian and successively Lower Triassic formations appearing from the west are combined into one hydrogeological structure due to sedimentary continuity on the regional scale. Their water-bearing capacity is mainly connected to the systems of fractures and fissures. The water-bearing sediments are sandstones, fractured mudstones, conglomerates and locally marly limestones, separated by numerous layers of clays and loams. In such a lithological setting, the aquifer is classified as a fissure and fissure–pore, separated by numerous poorly permeable layers.

On the western side, water-bearing formations are covered by Middle Triassic sediments developed from the bottom of the profile as carbonate conglomerates, sandstones, limestones and marls. Next in the sedimentary sequence, the Upper Triassic sediments are formed in the form of practically impermeable clays and mudstones, with some minor exceptions. Already in the first half of the 1990s, hydrogeological documentation defining disposable water resources in the vicinity of Kielce [34] recognized the northern fragments of the Permian–Triassic cover as a recharge zone for the northernmost Devonian reservoir MGWB No. 417 Kielce. The same sediments, however, together with far to the NW weakly permeable Lower Paleozoic formations of the Dyminy and Rykoszyn anticline, partially separating MGWB no. 417 from more southerly located MGWB no. 418, were regarded so far as providing sufficient isolation of both principal water-bearing structures. In all documentation and scientific publications to date, the two structures have been treated separately and analyzed independently. Separate, independent functioning digital hydrogeological models were developed for each of these structures [26,35–37], whose concepts and realized predictions originally did not raise any objections.

2.2. Mining Exploitation

Middle Devonian carbonate sediments, up to 1000 m thick, apart from a rich water reservoir, are also a valuable mineral. For several dozens of years, they have been intensively mined, becoming aggregate, fertilizer or raw material for cement and lime production. Both domestic and well-known global companies conduct mining activities here: CRH Materials Poland Ltd., Dyckerhoff Poland Ltd., Opencast Mines of Raw Materials for Roads S.A. in Kielce, Lafarge Aggregates Ltd., Świętokrzyskie Mineral Raw Materials Mines Ltd., and Nordkalk Ltd. However, the intensity of the activities varies greatly. Within the Kielce syncline and its recharge region, a large part of which is covered by urban development in Kielce and its outskirts, exploitation of rock materials is very local and is currently limited to two adjacent workings in the Laskowa Góra and Kostomłoty deposits, located to the NW of Kielce (Figure 1). The situation is completely different in the Gałęzice–Bolechowice–Borków syncline, located to the south. The land use is dominated by farmland, and in the eastern part by forests. Scattered buildings dominate, concentrated in a few villages. Only along the national road No. 73 there are buildings typical of urban suburbs, built by inhabitants of neighboring Kielce seeking more secluded places. This makes it possible to identify, document and exploit further deposits. Mining is concentrated in the central part of the syncline. On an area of about 27 km^2, four mines of different owners are adjacent to each other, conducting exploitation on 6 pits until recently. Currently, after the water reclamation of the Radkowice-Podwole pit [26], there are five operating, on the deposits: Jaźwica, Kowala, Kowala Mała, Trzuskawica (two pits Trzuskawica and Kowala; Figure 1). In the northwestern part of the structure, the Ostrówka deposit is in operation, and the neighboring Ołowianka-1 deposit is in the process of obtaining the necessary documents.

On average, about 10 million tons of raw materials are mined annually in the syncline, with less than a million in the adjacent structure [38]. Among the active six pits, the lowest mining ordinate of 150 m above sea level was reached at the Ostrówka deposit (Miedzianka mine). However, in the center of the structure, the ordinates of exploitation decrease to a maximum of 180 m a.s.l. Intensive and deep exploitation, depressing the water table to 103 m, requires pumping out on average annually about 28.5 million m^3 of water (78.14 thousand m^3/d; data for 2018). As a result of the superposition of local impacts, an extensive regional depression cone has formed, covering the vast majority of the structure, excluding the eastern part. At the peripheries of the Kielce syncline, the extraction of 0.88 million t of mineral is associated with the pumping of 1.92 million m^3 per year of water along with the lowering of the drainage ordinate to 219.5 m above sea level.

The exploitation of Ostrówka deposit, which is particularly important in the light of further considerations, reaches the deepest level, to the mentioned ordinate of 150 m above sea level. Lowering of water level by maximum of 103 m concerning its original location generates inflows of 34,400 m^3/d (12.6 million m^3 per year). Due to the depletion of resources, it is planned to start the exploitation of the neighboring Ołowianka-1 deposit, situated closer to the edge of the Mesozoic structure of the Holy Cross Mountains.

2.3. Characteristics of the Problem

The documentation works carried out for the preparation of Appendix no. 3 to the hydrogeological documentation establishing the exploitable resources of the municipal intake in Kielce—Białogon [36] brought unexpected results of measurements of the groundwater table position at some observation points. Consequently, the observed changes in the hydrodynamic field of strictly local character, after an in-depth analysis, caused a significant modification in the perception of groundwater circulation in the regional system. The basis for the reorientation of the concept of regional groundwater circulation, resulting from the distribution of hydrodynamic field, were the results of measurements of the groundwater table position of the Middle Devonian aquifer in three boreholes carried out in 2017 (out of a total of 67 boreholes measured for documentation).

The mentioned wells were drilled in the extreme southwestern part of the Kielce MGWB (Figure 3). In these three key boreholes, in the vicinity of Zagórze and Jaworznia villages, a decrease in the water table ordinates within the Devonian horizon was recorded by only 1.40 to 2.21 m, compared to the measurements from 2014. Although the changes were not large at first glance, they resulted in a change in the water table inclination towards the southwest, i.e., in the direction opposite to the center of the structure (where intake well drainage dominates) and in the formation of a local watershed.

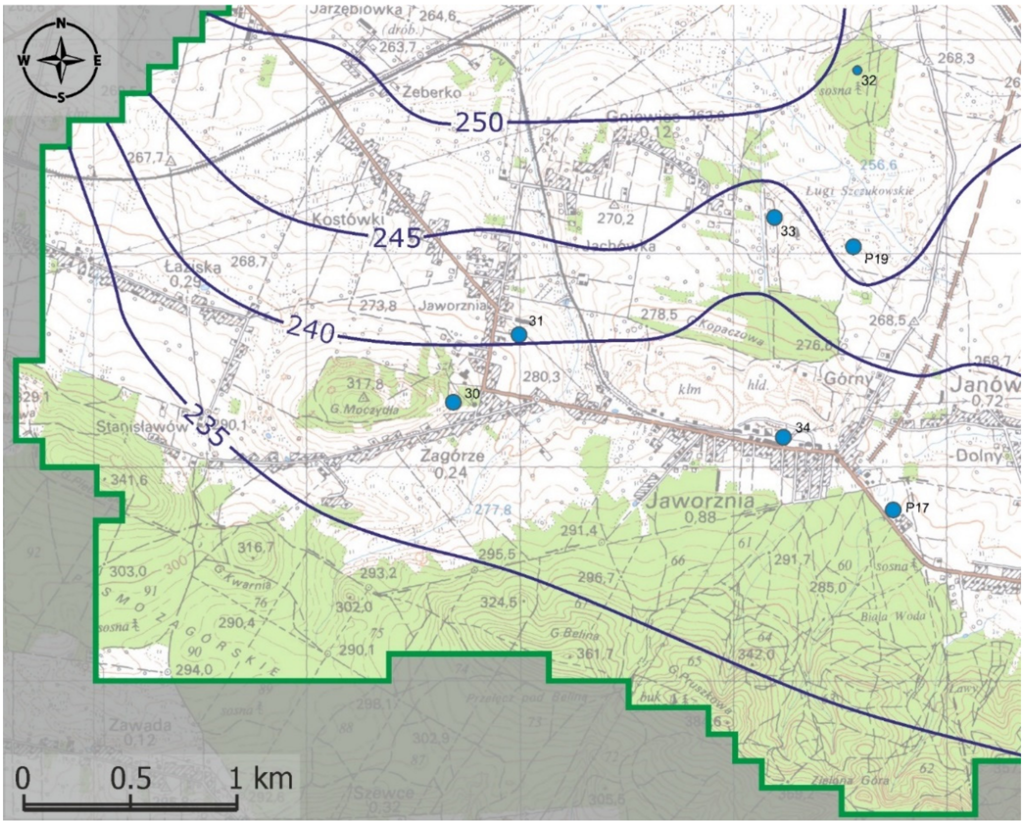

Figure 3. Hydrodynamic field layout (blue lines—groundwater table contours in m a.s.l.) with observation wells (light blue circles) in the SW part of the studied area. The state observed in 2017.

The first information suggesting the initiation of such a tendency appeared in the report summarizing the state of groundwater in the vicinity of the Białogon intake in 2016, prepared by Kielce Waterworks. Only the update of the regional hydrodynamic model of water circulation, carried out by the authors of the article in 2017, in connection with the need to update the intake's exploitation resources, allowed an in-depth analysis of the reasons for such an arrangement. As a consequence of the model calibration activities, the original assumptions of the concept of water circulation in the considered structure had to be changed, and the model itself was subjected to a relevant modification. A description of the implemented changes and the obtained effects is presented in Section 3.1.

The interpretation of the change in the direction of groundwater table inclination, contrary to the lean recorded for years towards the center of the structure, where the Białogon multi-well intake is located, resulted in the necessity to implement in the conceptual model an additional drainage center with significant impact, located in the direction opposite to the intake wells. The detailed analysis did not reveal the presence of other significant drainage facilities in the immediate vicinity. Individual wells, managed by local water users, were operated at low capacities. The nearest wells, located in Piekoszów, 2.5–3.5 km away towards the NWN (Figure 1), exploited approximately 100,000 m^3/a (Piekoszów

PGO well) and 160,000 m^3/a (Piekoszów well) from the Lower Devonian aquifer, averaging less than 450 m^3/d each (data from 2015 y., [37]). To the west, there are also some wells of the abandoned intake in Zawada, within sandstones of Lower Triassic and Permian age (about 2.5 km to the SW) and one more near the railroad station in Piekoszów (about 2.5 km to the NW, Figure 1). The latter drew the attention of the authors earlier, during work aimed at forecasting the volume of inflow to the "Ołowianka-1" Devonian dolomite deposit planned for resumption, in the vicinity of a large active mining site exploiting the "Ostrówka" deposit [37]. The hydrogeological model of the Gałęzice–Bolechowice–Borków syncline with MGWB No. 418 included the northwestern margin of the Devonian aquifer built of Permian and Triassic sediments (similarly to the surroundings of MGWB No. 417). The northern boundary of the model was drawn near Piekoszów, along the Czarne Stoki watercourse. Measurements of the water table position for the model calibration were conducted in June 2016. The measurements included a borehole near the railway station in Piekoszów, which had been inaccessible for a long time (secured by the owner), provided access to Triassic sandstones (T_1). After 39 years (data from the borehole drilling in 1977), the static water table decreased by 36.53 m to 214.97 m a.s.l. The same borehole was noticed by Prażak and his team [39], who, based on the results of archival measurements from the period of the borehole drilling, for the first time hypothesized that water filtration in the area of the borehole is directed towards the east, to the Bobrza River. However, at that time, the thesis was not confirmed by measurements.

On the other side, looking more broadly, data from a few wells located in the Piekoszów vicinity are not conclusive. The wells operated by ZUK in Piekoszów (outside the model area), adjacent to the PKP well from the north, despite their distance of about 2 km, i.e., twice less than the analyzed well to the "Ołowianka-1" deposit, show significantly different location of the water table. In the case of the "Piekoszów" well, the ordinate of the static water table reached 252.79 m above sea level, while in the case of the "Piekoszów PGO" well—251.93 m above sea level (June 2016). In the following year, measurements conducted to document the resources of the Białogon intake indicated ordinates of, respectively: 252.3 and 252.6 m a.s.l.

Even more controversial were the boreholes located further to the south, in the direction of the "Ostrówka" deposit drained to the level of 160 m a.s.l. (currently 150 m a.s.l.) and the planned reopening of the neighboring "Ołowianka-1" deposit (Figure 1). In Rykoszyn, measurements made in a private well with a depth of 34 m, filtered in Lower Triassic sediments, showed a static water table at the ordinate of 263.31 m a.s.l. (June 2016). Another borehole filtered in T_1 formations, near vicarage buildings in Rykoszyn, distant from the above-mentioned by 1 km towards E, with a depth of 39.5 m, has been dry for years (bottom ordinate 228 m a.s.l.). In turn, the mentioned intake in Zawada, consisting of two wells with a depth of 90 m each, drained Lower Triassic and Permian (Zechstein) sandstones. The approved resources of the intake are 9.7 m^3/h, with depression s_e = 22.0 m. Since the expiration of the water permit in 2006, the operation has been abandoned due to low yield and unfavorable hydrogeological parameters.

In the year 2018, Piekoszów municipality decided to build a new well to improve the water supply in the southern part of the commune. For the location of the new facility, a plot of land in the village of Lesica was chosen, less than 3 km to the NW from the edge of the pit. The 60 m deep well exploits the Middle Triassic limestone aquifer (T_2), which overlies the T_1 sediments to the west. After being drilled to a depth of 6.0 m, the water table rose by 0.6 m and stabilized at a depth of 5.4 m below the ground surface. The exploitation resources of the intake were determined to be 40.0 m^3/h, with a depression of 1.5 m. Operations began in the fourth quarter of 2018 with an average yield of approximately 260 m^3/d. Since then, the well has been operating undisturbed with more than double the average yield (660 m^3/d).

Such diverse and inconsistent information, obtained for the needs of various studies, has not always given sufficient attention to the peripherally located zone of Piekoszów. It was only when a well near the railway station in Piekoszów was unsealed for observation and different results of water table measurements were obtained in wells located in the SW part of the main groundwater basin Kielce (Jaworznia and Zagórze areas), that revealed the need to conduct a comprehensive analysis of numerous data from scattered boreholes and verification of the existing assumptions.

The key object for understanding the problem became the mine exploiting the Ostrówka deposit. The exploitation of the deposit historically linked to the Ołowianka deposit on the documentation stage, separated by the Hutka River valley, started in the late 1960s. The beginning of the exploitation is connected with the slope excavation, cutting the existing hill, starting from the ordinates of 290 m above sea level, within the highest sublevel of the floor I. The next floor II, at 236 m a.s.l., was dug below ground level in the classic form of an underground pit. Excavation was carried out using the longwall method with explosives. The encounter of the original water table took place slightly higher, at the ordinate of about 250 m above sea level, which was associated with the beginning of the pit drainage. With the opening of successive floors (221, 206, 192, 176 m asl), the depression increased, and the depression cone caused by it expanded. Initially, the depression did not extend beyond the Middle Devonian aquifer. With time, however, as it reached deeper resources, it entered laterally adjacent, poorly permeable Triassic strata, fringing together with younger Mesozoic sediments the Holy Cross Mountains (Figure 4A). Works focused at the ordinate of 160 m above sea level commenced in the middle of 2009. The increase with the deepening of the works inflow reached 31 thousand m^3/d (2015). A few years later, in 2015–2016, the lowering of the water table within the Lower Triassic formations, separating the Devonian syncline from the west, reached the region of Zagórze and Jaworznia, entering the SW part of the Devonian-filled Kielce syncline simultaneously (Figure 4B). The achieved state should be consolidated with the opening of the 8th level within the Ostrówka deposit, at the ordinate of 150 m a.s.l. in the third quarter of 2017.

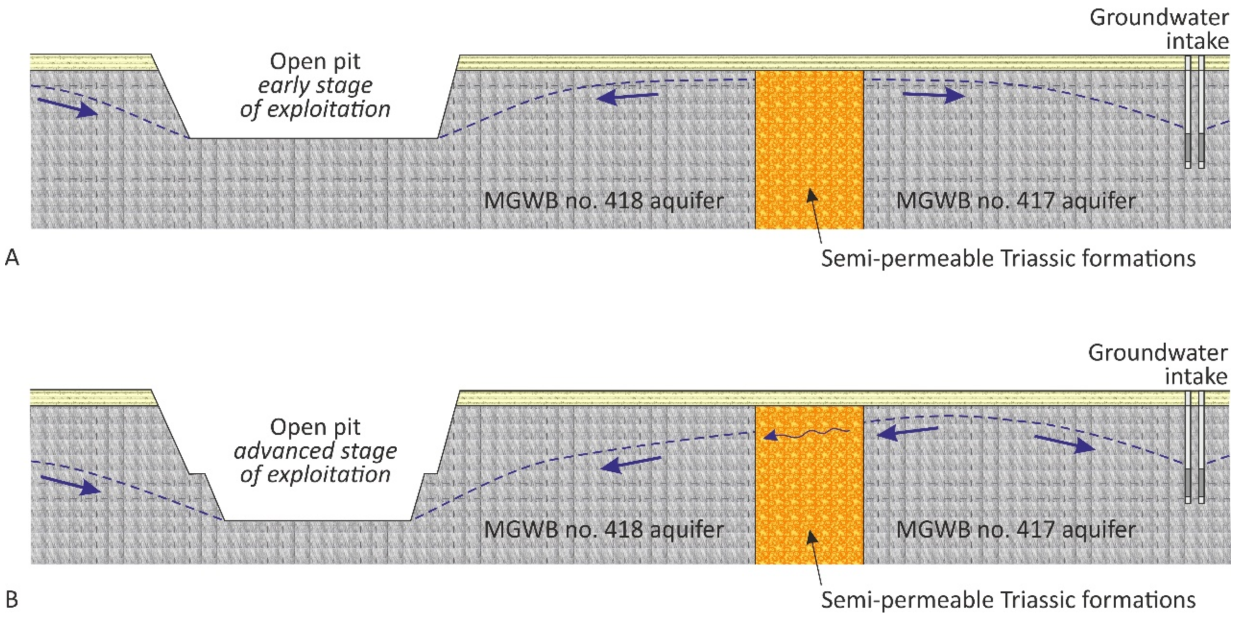

Figure 4. A schematic cross-section diagram of hydraulic connections between the considered hydrogeological structures (not to scale): early (**A**) and advanced (**B**) stages of open-pit exploitation. Blue dashed line—groundwater table; blue arrows—general directions of groundwater flow.

The Miedzianka mine has the right to exploit two neighboring deposits: "Ostrówka" and "Ołowianka 1". They are separated by the valley of the Hutka River. The object of exploitation is Middle Devonian limestones intended for the production of aggregates. Production within the active deposit "Ostrówka" requires pumping an average of 31 thousand m^3/d [37]. In June 2009, the seventh level was opened at the ordinate of 160 m a.s.l. Eight years later, in August 2017, the exploitation was lowered by another 10 m to the ordinate of 150 m a.s.l. At the deposit "Ołowianka 1", work was discontinued many years ago. Since 2016, preparations have begun to resume operations.

The Triassic aquifer is de facto a water-bearing complex, i.e., a system comprising more or less isolated water-bearing horizons developed in lithologically diversified Triassic layers. The water-bearing horizons include the clastic formations of the Bunter sandstone, carbonates of its highest part—the Röt—as well as carbonates of the middle Triassic—the Muschelkalk. The younger and younger formations appear on the surface towards the west, eventually disappearing under the cover of impermeable formations of Carnian. Amongst the clastic formations of the Bunter sandstone, the reservoir rocks are sandstones with interbedding clays and siltstones with porosity of about 8 to 20% (average 15%), as well as limestones of the highest part of the Lower Triassic—the Röt. Sandstones, characterized by large variability in porosity and fracturing, have correspondingly different hydrogeological parameters. Particularly high variability is observed in hydraulic conductivity, generally ranging from 9×10^{-8} to 3.6×10^{-4} m/s (0.008 ÷ 31.1 m/d, [40]). With variable thickness, transmissivity values range from 1 to more than 1400 m^2/d. The Lower Triassic aquifer is unconfined in outcrop areas, changing to subartesian in the remaining areas. The isolating layers causing an increase in pressure are clay inserts overlying sandstones.

Muschelkalk limestones and dolomites, with thicknesses in the range of 20 ÷ 150 m, are fractured and karstified. They attain higher hydraulic conductivity than those of the Bunter sandstone, ranging from 1.7×10^{-6} to 1.6×10^{-4} m/s (0.15 ÷ 13.8 m/d, [40]). Similarly, as in the case of the Bunter sandstone aquifer, the Muschelkalk limestone aquifer generally remains unconfined in the outcrop areas, changing its character to confined in the zones where it occurs under the cover of poorly permeable Upper Triassic (Carnian) formations, stabilizing at depths from a few to a maximum of several meters.

A significant degree of complexity of the aquifer system, with a simultaneously limited amount of hydrogeological information concerning water-bearing capacity and, in particular, hydraulic contacts of individual layers with each other and with neighboring units, significantly hinders the unambiguous representation of the details of the geological structure on the hydrodynamic model.

2.4. Study Area

Municipal intake at Kielce—Białogon covered by the research areas, together with the area of recharge, is located in the voivodeship Świętokrzyskie, in the area of Kielce city and neighboring communes: Strawczyn, Miedziana Góra, Masłów, Górno, Daleszyce, Sitkówka-Nowiny, and Piekoszów (Figure 5). Municipal intake at Kielce—Białogon supplies drinking water to Kielce agglomeration. All wells are administratively located within the city limits of Kielce, in the southern district—Białogon. The wells are located on the left bank of the middle course of the Bobrza River, in the area of the mouths of Sufraganiec and Silnica tributaries. River drainage generally directs water from north to south. The ordinates of the land at the well sites are in the range 238–247 m a.s.l. The major aim of the completed hydrogeological model tests was to present system of groundwater circulation in the area for updating exploitable resources of the groundwater intake in Kielce—Białogon as well as to define the range of protection zone around it.

The Kielce—Białogon intake is a multi-well intake. It consists of 21 deep wells, 15 of which have water permits for water abstraction. Six wells are not exploited and serve as observation wells. The productive wells draw water from part of the aquifer limited to the MGWB no. 417 Kielce. The intake provides water for 64% of consumers in the city, belonging to the water supply system of Kielce based on three large groundwater intakes supported by emergency intakes. Water intake from deep wells started in 1956 (approx. 150 m^3/h) and systematically increased until 1990 when it reached an average of 1555 m^3/h. In the following years, the intake gradually decreased, and in the last year preceding the implementation of the presented works (2016) reached an average of 899 m^3/h.

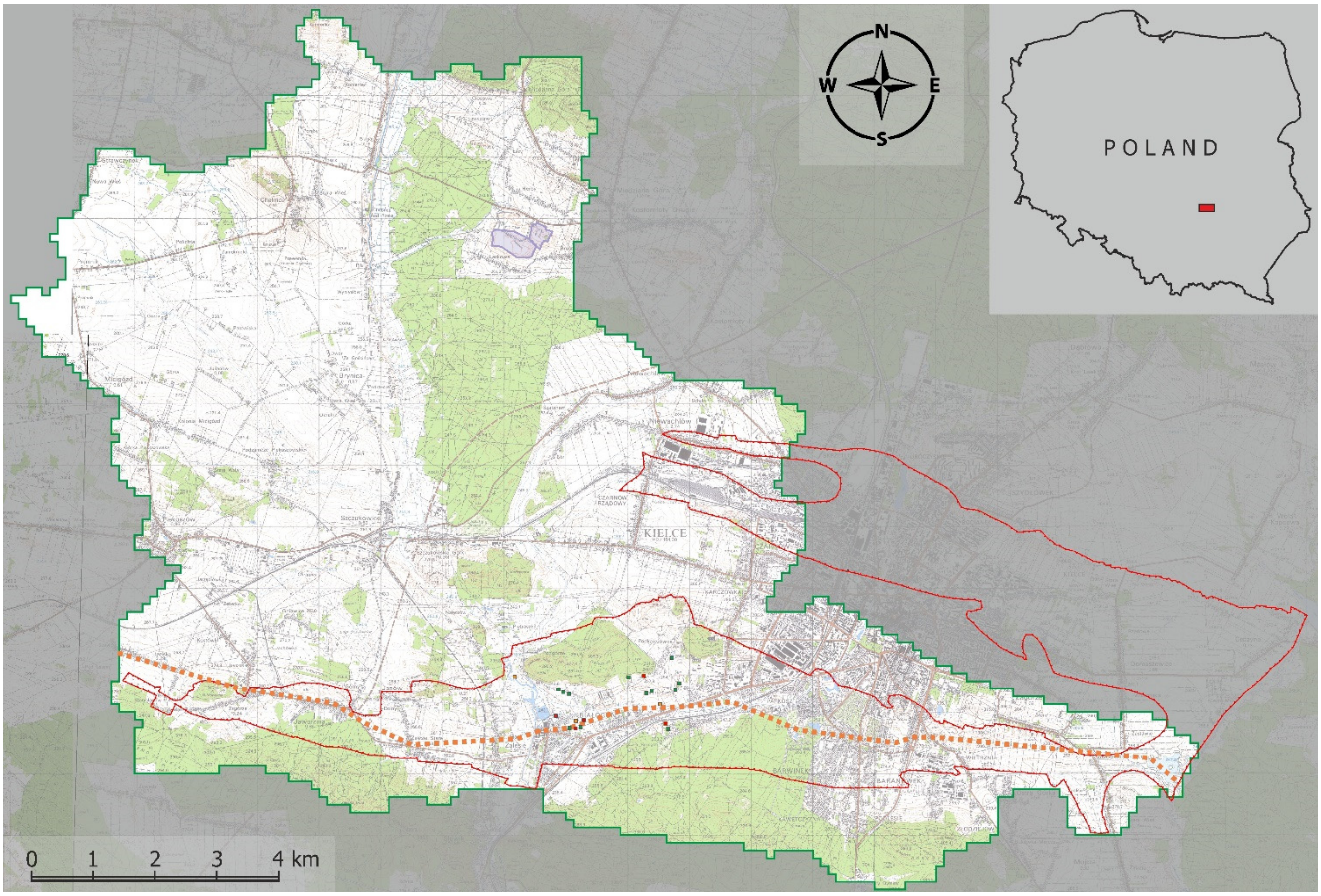

Figure 5. Modelled area of the MGWB No. 417 with schematic geological boundaries (red lines), location of open-pit mines (light purple), cross-section line (orange dotted line) and exploitation wells (color dots). Geology and cross-section according to [34].

2.5. Numerical Model of Hydrogeological Conditions

The numerical hydrogeological model, which allowed determining the resources of the intake, was prepared based on the multilayer hydrogeological model of the Kielce Groundwater Exploitation Area—Subdivision A [41], which has been in operation for several years, in the updated version for 2015 as part of the realization of the "Supplement to the Hydrogeological Documentation ... " [42]. The model was updated to a state corresponding to the averaged intake exploitation from 2016 and the results of groundwater table position measurements conducted in mid-2017. The discussed model includes the so-called Kielce Groundwater Exploitation Region—balancing subregion A. The groundwaters in this region are mainly exploited from the Middle Devonian aquifer MGWB 417 Kielce, southern wing of the Kielce syncline, and also, in smaller quantities, by individual wells, from Middle Permian and Lower Triassic, as well as Upper Devonian and Middle Triassic aquifers situated in the water recharge zone from the north [41].

The numerical multi-layer model of groundwater flow (6 layers) was prepared using the Processing Modflow program [43], which is based on the original MODFLOW code [27]. The model study covered an area of about 130 km^2. The archival version was reconstructed based on the results of direct research and field measurements. The boundaries of the so-called subregion A refer to natural boundaries of hydrodynamic nature, associated with groundwater watersheds or rivers (Figure 5). The model retains the concept of schematization of hydrogeological conditions adopted in the original hydrogeological model [41]. Horizontally, the model study area was discretized based on a regular grid (125 × 125 m square cells). An active part of the modelled area is contained in a rectangle comprising of 114 rows and 155 columns, which corresponds to the real size of about 14.3 × 19.4 km.

Layer 1 (Figure 6) represents water-bearing near-surface Quaternary formations and water-bearing or poorly permeable older formations outcropping or occurring under a cover of Quaternary formations of small thickness (aeration zone). Layer 2 corresponds to poorly permeable Quaternary and Neogen formations (clays, loams, silts) and poorly permeable older formations outcropping or occurring under a cover of Quaternary formations of low thickness. The purpose of layers 3, 4, 5 and 6 is to map water-bearing formations of older bedrock (D_2, D_3, P_2, T_1, T_2) and, in the peripheral parts of the model, poorly permeable formations of older Palaeozoic (Cm, O, S, D_1) as well as Upper Triassic. Together, these layers constitute the principal useful aquifer.

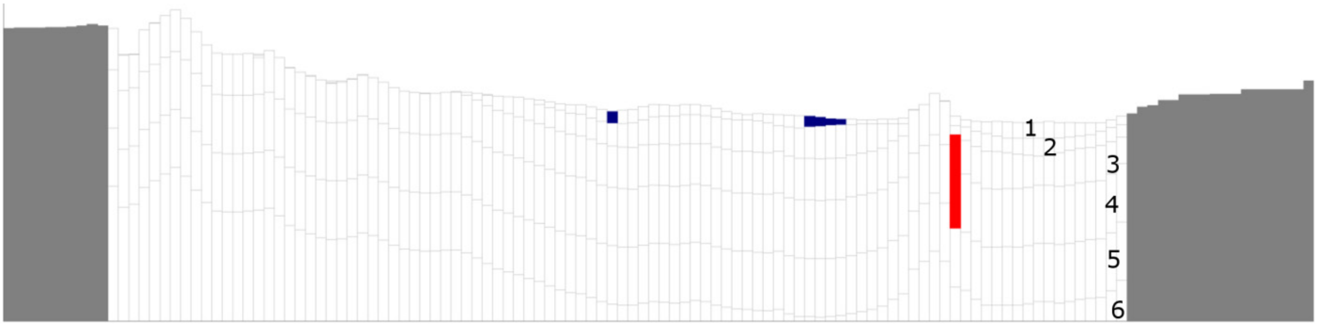

Figure 6. Scheme of vertical discretization into model layers (layer numbering was marked); example cross-section along column 80, vertical exaggeration—10. The meaning of the colors in the cells: white—active, grey—inactive, blue—first-type boundary conditions (some rivers), red—second-type boundary condition (exploitation wells).

In all layers, active cells were defined, corresponding to filtration area (Figure 7—white cells), and inactive cells, not taking part in computation process (Figure 7—grey cells). For rivers with good hydraulic contact between surface water and groundwater (Bobrza, Sufraganiec, part of Lubrzanka), boundary conditions of first-type H = const were assumed within layer 1 (Figure 7—blue cells). The same condition was assumed for layer 4 in cells corresponding to the location of the Laskowa mine workings, which allows for simulation of its dewatering. Due to the limited hydraulic contact between surface- and groundwater, the remaining smaller watercourses were simulated with the boundary conditions of the third type using RIVER package (Figure 7—light blue cells). Parameters assigned to individual cells in the RIVER module (hydraulic conductance of the riverbed) take into account both the hydraulic conductivity of the riverbed bottom sediments, their thickness and the size of the river in individual calculation cells. In addition, a graded head in the river and elevation of the riverbed bottom parameters were established.

The values of hydraulic conductivity (horizontal and vertical) corresponding to the modelled aquifers were entered into the cell zones and then modified during model calibration. The karst phenomena typical of carbonate aquifers have been documented, although their recognition is irregular and only local [44]. Taking into account the regional scale of the research and the degree of discretization (cell size), the model calculations were based on the values of parameters typical of fissure–karst–pore aquifers. The distribution of hydraulic conductivity of individual layers obtained after model calibration is presented in Table 1. It should be considered that extreme values usually occur only locally, in places with specific geological conditions.

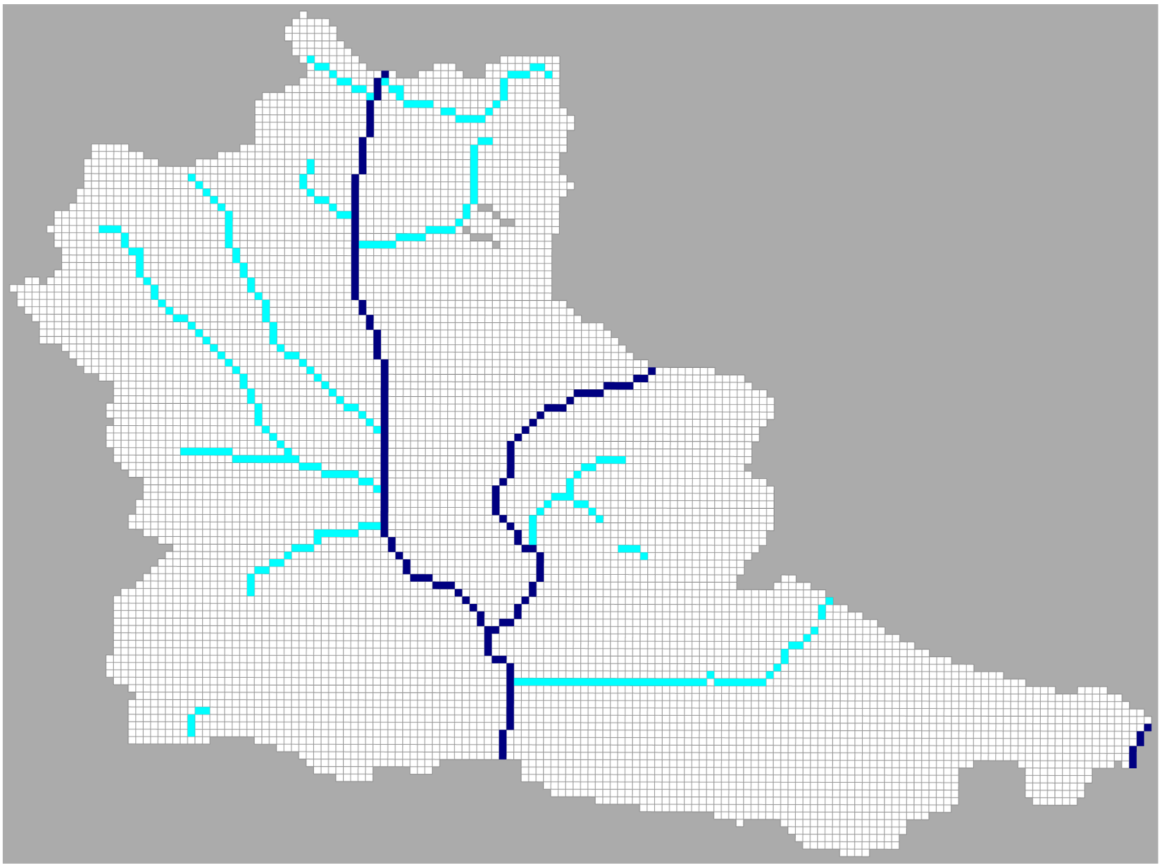

Figure 7. Cell status within layer 1 at the model calibration stage (white—active cells; grey—inactive; blue—rivers with good hydraulic contact with groundwater, I type boundary condition; light blue—rivers with limited hydraulic contact with groundwater, III type boundary condition).

Table 1. Variation in hydraulic conductivity in different model layers, after model calibration.

Layer	**Hydraulic Conductivity [m/d]**			
	Minimum	**Average**	**Median**	**Maximum**
1	1.89×10^{-3}	1.78	0.43	30.24
2	1.36×10^{-3}	0.46	7.75×10^{-3}	43.20
3	6.71×10^{-4}	6.73	1.73	82.08
4	6.71×10^{-4}	6.75	1.73	82.08
5	6.71×10^{-4}	6.59	1.73	82.08
6	6.71×10^{-4}	6.61	1.73	82.08

Effective recharge of precipitation depends on the magnitude of precipitation and effective infiltration coefficient. In practical groundwater modeling, typically the so-called effective recharge (the amount of water that enters the rock mass) is adopted, ignoring the evaporation. Before model calibration, an effective recharge was estimated, based on average annual precipitation recorded for Kielce (629 mm, [45]), the permeability of subsurface sediments and types of land development. Then, recharge from precipitation was assumed as a second-type boundary condition (Q = const), using the RECHARGE package with the option Recharge is applied to the highest active cells. After model calibration, the average amount of effective recharge from precipitation was 3.36×10^{-4} $m^3/d/m^2$ (Table 2), which is about 20% of the average annual rainfall in the Kielce region. The size of the infiltration rate varies depending on the permeability of the rocks present in the near-surface layers, the degree of land development and the location within the range of the depression cones of the Laskowa mine and groundwater intakes.

Table 2. Variation in effective recharge, after model calibration.

Unit	Effective Recharge			
	Minimum	**Average**	**Median**	**Maximum**
m/d (m^3/d/1 m^2)	8.33×10^{-5}	3.36×10^{-4}	3.77×10^{-4}	6.51×10^{-4}
mm/year	30	123	138	238
L/s/km^2	0.96	3.89	4.36	7.53

Intake wells with a constant yield were simulated using the second-type boundary conditions (Q = const). The model includes numerous deep wells, from which regular water abstraction was carried out in 2016. Constant yields from wells, defined as daily averages based on the actually registered abstraction in 2016, were assumed to total 25,029 m^3/d, within layer 3 (Figure 8A) and layer 4 (Figure 8B). Most of the wells work in cooperative conditions, remaining under the hydrodynamic influence of adjacent intakes.

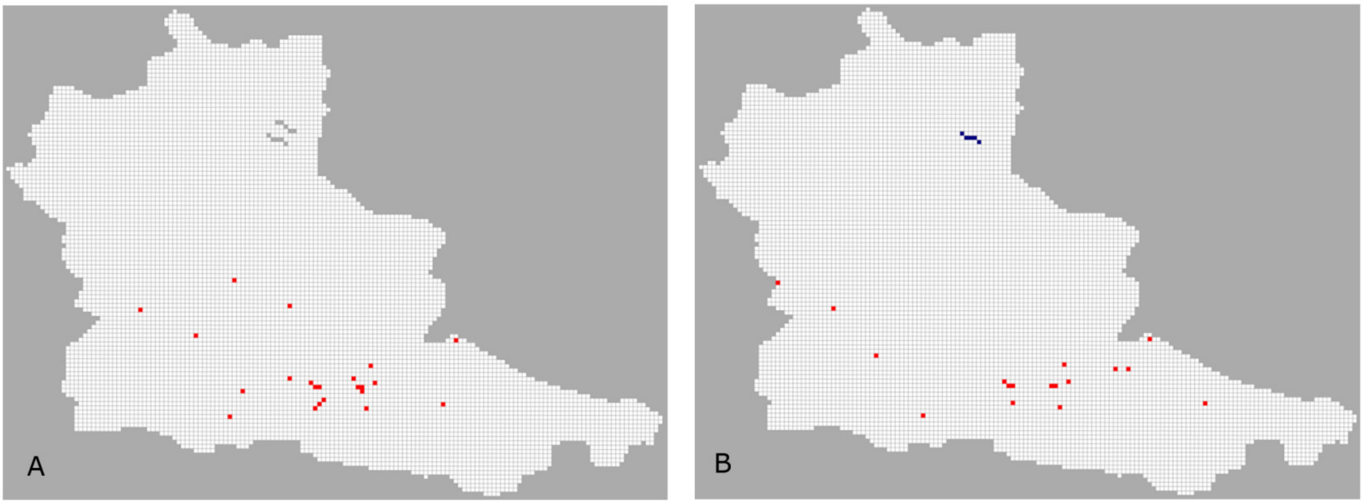

Figure 8. Location of production wells (red cells) within the 3rd (**A**) and 4th (**B**) model layers.

Prognostic calculations were performed under steady-state flow simulation. This research method comes down to the determination of the target state resulting from the assumed stresses, without indicating any intermediate states that characterize the temporal variability of the considered phenomenon.

2.6. Model Calibration and External Influence of Mine Activity

For numerical calculations of groundwater filtration equations, a simulator based on the finite differences method (FDM) from the widely used MODFLOW family [11] was used, with MODFLOW-2005 [27] being the most commonly used version at present. The prepared model was subjected to a calibration process, the aim of which was to obtain accordance between hydraulic heights obtained from model studies and those measured during field mapping, as well as between inflows to the Laskowa pit simulated in the model and those measured in reality. For the calibration results of own field measurements of the groundwater table depth in 67 boreholes were used, carried out in July 2016. After analysis, a selection of measurement points was made; finally, for calibration, water table location information was used from 42 boreholes not operating or water abstraction was marginal.

The trial-and-error method [11] was applied to calibrate the model. During the calibration, the spatial distribution of hydraulic conductivity was modified. Slight changes were also made in values of vertical hydraulic conductivity which co-determines the amount of seepage between individual layers. As part of the calibration, also the recharge from precipitation infiltration was corrected. In addition, the hydraulic conductance of the riverbed, which determines the contact of surface water with groundwater, was slightly modified.

The results of the own field measurements of the groundwater table position from July 2016 and previous hydrogeological measurements (2015) in municipal wells and piezometers under local monitoring conducted by Kielce Waterworks clearly indicate that the hydrodynamic field in a part of the considered area had changed compared to previous observations and interpretations [41]. Monitored points located in the southwestern region of the modeled structure (30, P17) indicate lower water table ordinates than points closer to the Kielce—Białogon intake, e.g., 37, P8, P8A, V (Figure 3). Since in the southwestern region of the studied aquifer the exploitation of groundwater is not intensive (Section 2.3) and the existing watercourses are not capable of producing such a lowering of the water table, the only explanation is the drainage of strata occurring outside the area of direct model tests, where size and extent affect the hydrodynamic field system in the area under consideration. The analysis of the archival materials and documentary studies leads to the conclusion that the existing layout of the water table is most probably influenced by a large drainage center in the "Ostrówka" deposit exploited by the Miedzianka mine located some distance to the southwest (Figure 1). Due to the location of the mine in a separate hydrogeological aquifer (Gałęzice–Bolechowice–Borków syncline), previous studies assumed its very limited influence on other neighboring structures. Current measurements, however, indicate that such influence, although relatively small, is noticeable, reaches other water-bearing structures and cannot be ignored in the considered issues. The original lack of water exchange between the two adjacent hydrogeological structures likely could have been disturbed by intensive mining drainage of the Miedzianka mine workings (nearly 1300 m^3/h), significantly larger than the groundwater abstraction by the Białogon intake (about 900 m^3/h; [36,37]). The influence of such drainage could be revealed after a sufficiently long time and further lowering of the drainage ordinate in the Ostrówka pit, in the form of a locally different than originally shaped water table in the Kielce Groundwater Exploitation Region, causing relatively small groundwater flows between structures.

It was necessary to include in the model the influence of external stressing factors coming from outside the modeled area. For this purpose, the General-Head Boundary module [43] was used, which allows for mapping with third-type boundary condition of external stresses. In the extreme blocks of the model from the southwestern side (Figure 9), in layers mapping older formations (3, 4, 5 and 6), conductivity to a distant boundary, calculated taking into account low values of filtration parameters and distance of the mine from the model, as well as ordinate of the water table in the drained pit (160 m above sea level), was assumed. During further calibration, the adopted values of conductivity were locally slightly modified. A detailed description of the results of measurements taken from wells situated in the area of the probable impact of drainage of the neighboring structure (SW part of the Major Groundwater Basin in Kielce) is given in Section 2.3.

As a result of the calibration, a numerical hydrogeological model was developed, that generates the results (the water table arrangement and the flow to dewatered Laskowa excavation) similar to those observed in reality (the so-called Variant 0—current hydrodynamic state after model calibration). For the adopted calibration points, the differences between the measured water table and obtained by interpolating the resulting matrix distribution from the model are insignificant and, in principle, do not exceed the value of a single meter. The arrangement of the measurement points directly adjacent to the diagonal of the calibration plot (Figure 10) means a good fit of the model's response to the actual observations.

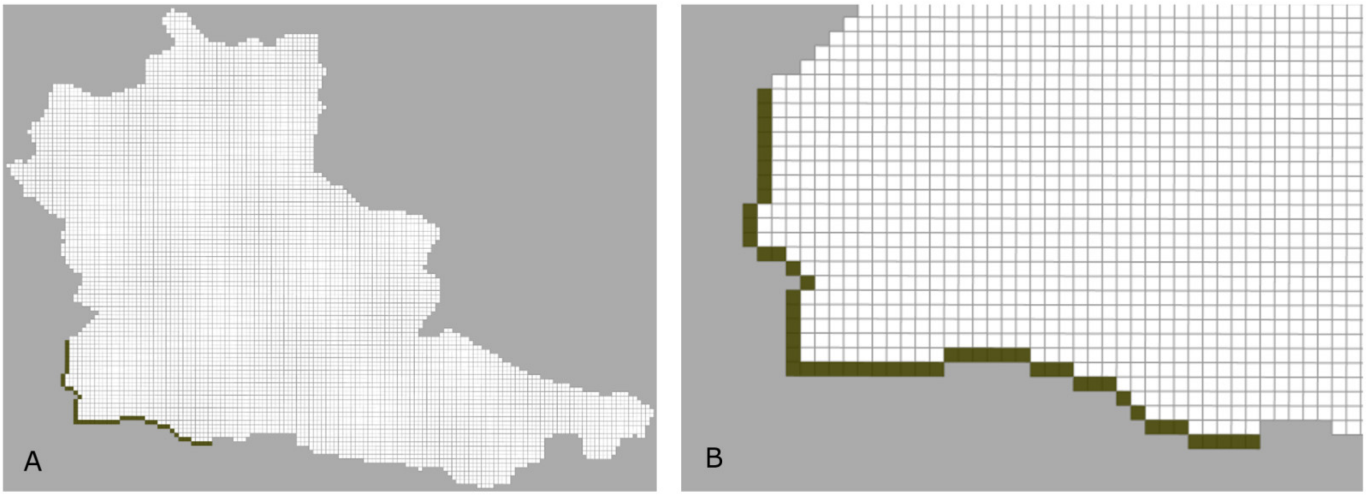

Figure 9. Location of the General-Head Boundary (dirty green cells) within the 3rd, 4th, 5th and 6th layer: whole model (**A**) and SW part of the model (**B**).

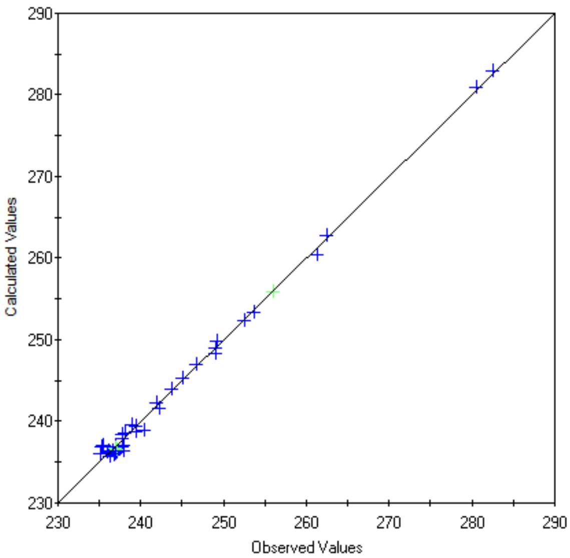

Figure 10. Comparison of the water table ordinates [m a.s.l.] obtained from the model (calculated values) and those observed in reality (observed values) for the adopted calibration points (blue—Middle Devonian, green—Quaternary).

Considered as calibration criteria, the error rates are: mean error *ME* = 0.13 m, mean absolute error *MAE* = 0.57 m. Normalized value is related to the amplitude of water table fluctuation in the considered structure (approx. 80 m); mean absolute error value does not exceed 1%. The volumes of inflows to the Laskowa open pit obtained from the model after calibration (5271 m^3/d) concerning inflows observed in the year 2016 (5261 m^3/d) differ to a very small extent.

3. Results

3.1. Reconstructed Current State (Variant 0)

The total amount of water circulating in the considered structure for Variant 0 (reconstructed current state) is approximately 49,242 m^3/d (Table 3). From the inflow side, this value is primarily determined by the effective infiltration of atmospheric precipitation (approx. 43,385 m^3/d), while the remaining part consists of infiltration of water from surface watercourses (about 5856 m^3/d). Rivers are more of a drainage nature, changing locally into infiltration in places where mine or groundwater intakes have a drainage effect.

On the outflow side, the dominant factors are drainage of groundwater intakes (about 25,029 m^3/d), outflow to surface watercourses (about 15,563 m^3/d), and, to a lesser extent, drainage of open-pit mines (about 5272 m^3/d). In addition, on the drainage side, the outflow to the adjacent hydrogeological structure was taken into account, with an average amount of 3378 m^3/d. This is the amount of water drained as a result of the impact of the large Miedzianka open-pit mine located in the neighboring structure, the direct impact of which was not taken into account in earlier studies.

Table 3. Summary of water circulation balance obtained based on model research.

Component	Inflow/Outflow [m^3/d]					
	Calibrated		Prognosed			
	Variant 0 (Calibrated)		Variant 1 (Pseudo-Natural)		Variant 2 (Groundwater Resources)	
	In	Out	In	Out	In	Out
Effective infiltration of atmospheric precipitation	43,385	0	43,423	0	43,385	0
River infiltration/drainage	5856	15,563	491	43,915	8836	11,757
Exploitation of groundwater intakes	0	25,029	0	0	0	31,906
Drainage of open-pit mine	0	5272	0	0	0	5222
Lateral exchange with an adjacent structure	0	3378	0	0	0	3336
Total	49,242	49,242	43,915	43,915	52,221	52,221

An assessment of the hydrodynamic field distribution was carried out for the main exploitable aquifer (layers 3, 4, 5, and 6). Layer no. 3, within which a major part of groundwater exploitation is carried out, was assumed to be representative of the whole complex (Figure 11). The shape of the hydrodynamic field results from the functioning of several drainage systems. In the central part, a relatively large range of the lowered water table zone is related to the operation of exploitation wells of the municipal intake Kielce-Białogon. Due to a large, but relatively even, water uptake, the hydraulic drop is small, and in the vicinity of the well, the water table usually reaches the ordinate of 235.5–236.0 m above sea level. In the northern part of the modelled structure, in a small zone around the Laskowa mine, the hydraulic gradient of groundwater is higher as a result of an excavation dewatering at an ordinate several dozen meters lower than the surroundings (~220 m a.s.l.). In the southwestern part, an outflow towards the Miedzianka mine, situated outside the modelled area, is clearly visible. Initially, the hydraulic gradient is small (the water table in the area of boreholes 30 and P17 is about 235 m a.s.l.). In the direction of the distant mine, which is drained at the level of 160 m a.s.l., the hydraulic gradient of groundwater increases; in the extreme SW corner of the model, the water table decreases to the level of about 220 m a.s.l. In the central part, the regional groundwater flow directions are strongly influenced by the Bobrza River, mapped within the Quaternary layer by first-type boundary conditions.

3.2. Prognostic Variants

3.2.1. Assumptions

Prognostic simulations were performed for two variants (numbers 1 and 2). The assumption of variant 1 was to recreate the original conditions of water circulation in the modelled structure, undisturbed by anthropogenic impacts (pseudo-natural state). Preparation of the model for such a state required the deactivation of modules responsible for the simulation of exploitation of groundwater intakes, dewatering of the mine workings and lateral outflow to the neighboring structure.

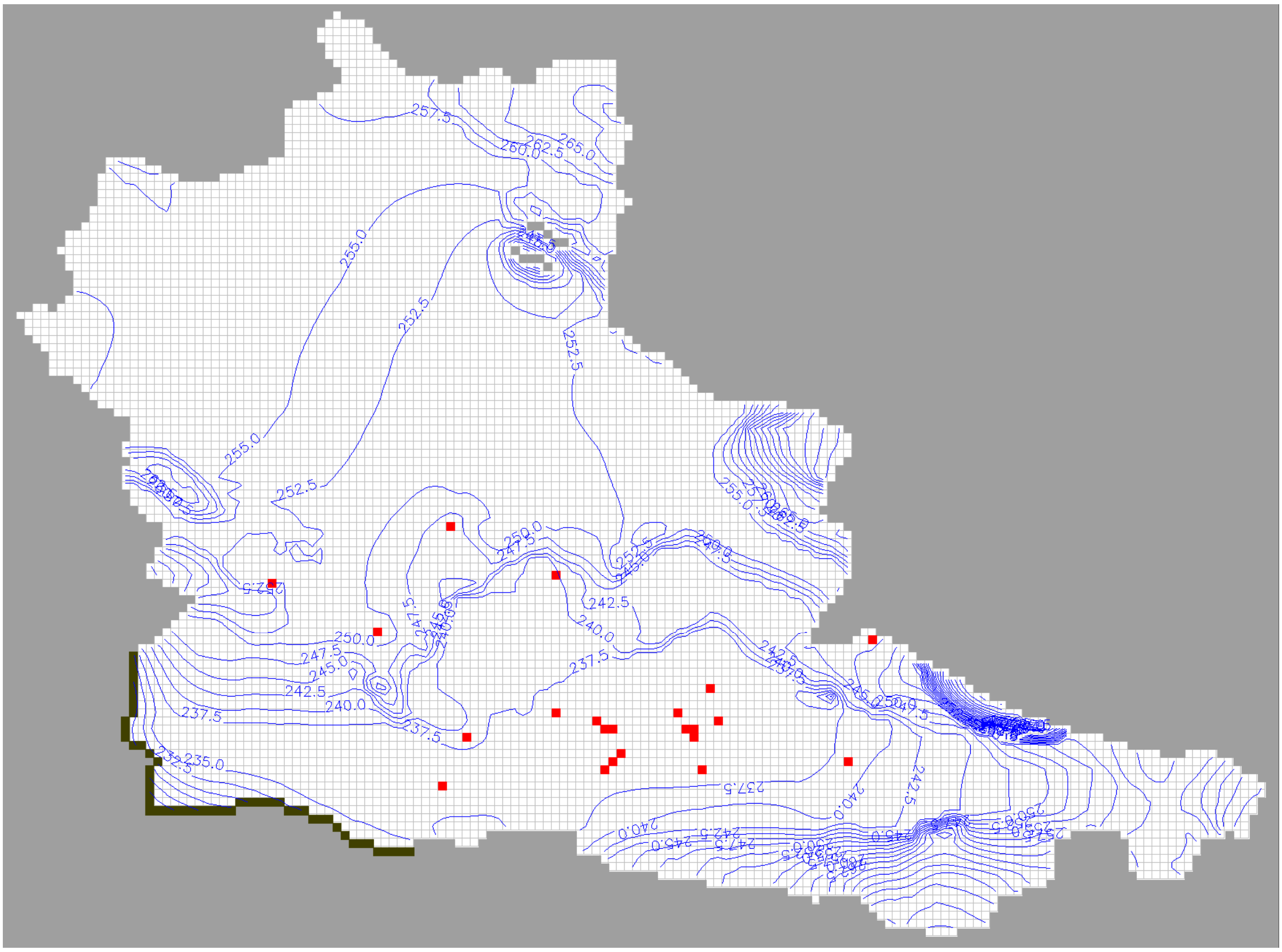

Figure 11. Hydrodynamic field distribution (blue lines—groundwater table contours in m a.s.l.) of the principal useful aquifer (Layer 3). Variant 0—calibrated state (mid-2017).

The assumption for variant 2 was to simulate the impact of the exploitation of groundwater intakes with flow rates corresponding to those approved in water permits. For the Kielce—-Białogon intake, the assumed total well flow rate is 24,960 m^3/d. The remaining stresses in comparison with the calibrated state (variant 0) did not change. The obtained results of simulation calculations should be treated as indicative and their validity should be considered for a longer period.

3.2.2. Variant 1

The obtained results are presented in the form of an aggregative water circulation balance (Table 3) and a map of the hydroisohypses of the principal exploitable aquifer (Figure 12A). The total volume of circulating water in the analyzed structure for variant 1 reaches about 43,915 m^3/d. On the recharge side, this value consists primarily of effective precipitation infiltration of 43,423 m^3/d. The remaining, small part of recharge is formed by infiltration of water from surface watercourses, in the amount of 491 m^3/d. On the other side, the only component of the balance (100%) is drainage by surface watercourses, in the amount of 43,915 m^3/d. In reference to the present conditions (variant 0), the results of simulations for the pseudo-natural state (variant 1) indicate the definitely greater role of watercourses, both on the recharge side (12-fold decrease) and on the drainage side (nearly 3-fold increase, absolute domination in values). The total volume of circulating water in variant 1 (pseudo-natural) is lower by about 5327 m^3/d in comparison with variant 0.

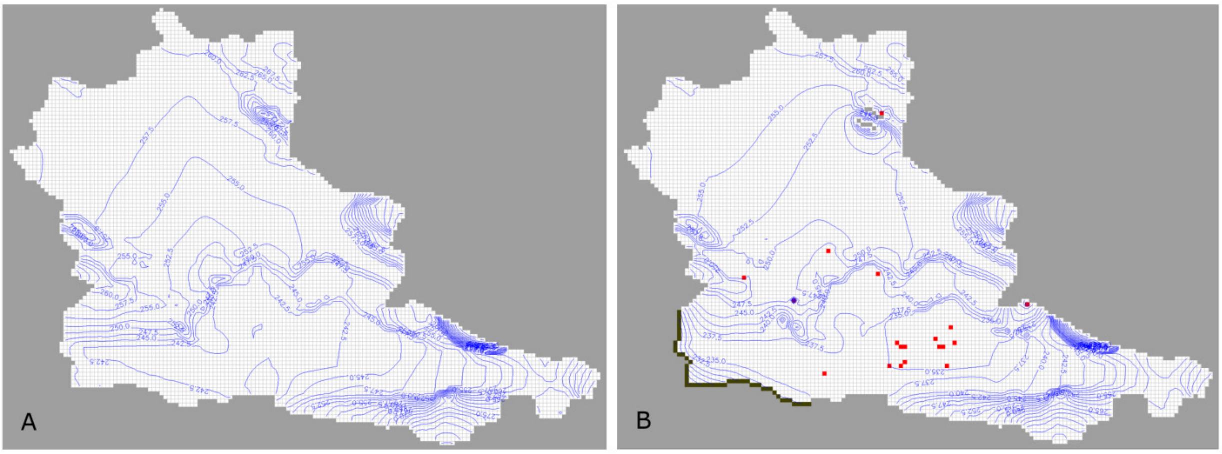

Figure 12. Hydrodynamic field distribution (blue lines—groundwater table contours in m a.s.l.) of the principal useful aquifer (Layer 3): variant 1—pseudo-natural state (**A**) and variant 2—groundwater resources prognosis (**B**).

In the assessment of the hydrodynamic field distribution in the modeled main aquifer, a dominant role of draining character of the Bobrza River can be observed (Figure 12A). In general, the groundwater flows either directly to the Bobrza valley or locally through smaller watercourses.

3.2.3. Variant 2

In variant 2, the total amount of water circulating in the considered structure is about 52,221 m^3/d (Table 3). This quantity on the recharge side consists primarily of effective precipitation infiltration of 43,385 m^3/d. The remaining part of the recharge is formed by the infiltration of water from surface watercourses (8836 m^3/d). On the drainage side, the exploitation of groundwater intakes dominates, with a total yield of 31,906 m^3/d. The second most important factor on the outflow side can be assumed as drainage by surface watercourses at 11,757 m^3/d. To a much lesser extent, the hydrostructure is drained by the Laskowa pit dewatering system (5222 m^3/d). The smallest share in regional drainage has lateral outflow to the neighboring hydrogeological structure—towards the Miedzianka mine (3336 m^3/d). The assessment of hydrodynamic field distribution in a main useful aquifer was based on the results for a representative layer no. 3, within which the major part of groundwater exploitation is carried out (Figure 12B). The hydrodynamic field arrangement obtained in the prognosis results from the functioning of several drainage systems. In the central part, the largest decrease in the water table is connected with the anticipated exploitation of the municipal intake in Kielce—Białogon. In the vicinity of wells, the water table reaches the ordinate of about 234.0 m a.s.l., which means a decrease in comparison with the present state (variant 0) by about 1.5–2.0 m. The horizontal range of the lowered pressure zone is slightly increasing, mainly towards the east and south.

In the northern part of the modeled structure, as a result of further exploitation of the Laskowa Mine, a lower-pressure zone is anticipated to form. The hydrogeological watershed between the drainage centers of Laskowa and Kielce—Białogon is shaped about 2 km away from the south edge of the excavation. In the southwestern part, the hydroisohypse configuration indicates the outflow of groundwater in the direction of the Miedzianka mine, which is situated outside the modeled area. Similarly, as in calculations for variant 0, in the direction of the distant Miedzianka mine, the hydraulic gradient increases while consequently, the water table decreases to the ordinate of about 220 m a.s.l. in the extreme SW corner of the model.

4. Discussion

The measurement data collected in 2016 to update the model of the Kielce supply region (including MGWB no. 417) showed a a slight, but significant in consequences, local change in the position of the groundwater table. Apart from model calibration, it became necessary to modify the general assumptions described in the previous sections. Former studies (e.g., [35,41,46]) assumed independent circulation of groundwater in the neighboring basins (MGWB) no. 417 and 418. This was justified by the lack of any measurement data, that could indicate the lateral exchange of water between the hydrostructures. The studies on groundwater table arrangement in both units did not suggest any possibility of lateral water exchange between them.

Within the limits of MGWB Kielce (no. 417), together with the recharge zone within the northern Permian–Mesozoic margin sediments of the Holy Cross Mountains, 49,242 m^3/d of water circulate, according to the model studies of 2017 [36], as presented in Section 3.1. Recharge from effective infiltration of precipitation dominates with a share of 88.1%, supplemented by infiltration from surface watercourses (11.9%). On the drainage side, the water balance is dominated by the exploitation of groundwater intakes, with a total capacity of 25,029 m^3/d, which corresponds to 50.8% of the drainage of the whole structure. Within intakes, the most significant role is played by the multi-well intake at Kielce—Białogon. According to 2016 data, the other intakes produced an average of 3276.9 m^3/d, which constituted only 13.1% of the total abstraction. The second element on the outflow side in terms of quantity (31.6%) is drainage by surface watercourses in the amount of 15,563 m^3/d, followed by mining drainage (10.7%), represented by a single open-pit Laskowa, exploiting the Devonian dolomites for aggregate production. The second one, Kostomłoty, extracts raw materials in the zone above the groundwater table, taking advantage of its location in the vicinity of the deeper neighbor. As a result of the conducted studies, another factor was included in the model, related to lateral outflow to the neighboring hydrogeological structure towards Miedzianka mine on the Ostrówka deposit (3378 m^3/d), which corresponds to a 6,9% share of the outflow side.

The water balance is shaped differently in the adjacent to the south structure of the Major Groundwater Basin no. 418, together with the northwestern zone of the Permian–Mesozoic margin. The dominant drainage element here is mining drainage, whose significant scale induces intensified infiltration of river waters into the aquifer. With a total volume of circulating water in the considered structure (variant 0) of 138.7 thousand m^3/d, according to model studies of 2020 [46], the contribution of precipitation to recharge decreases to 71.8% of the total revenue, while the share of river water infiltration accounts for 25.8%. The updated version of the Gałęzice–Bolechowice–Borków syncline model (including MGWB no. 418) has already taken into account lateral inflow from the neighboring structure, as revealed during the 2017 study. The share of the component deriving from this inflow in the total supply was estimated at 2.4%, or 3.4 thousand m^3/d.

On the other side of the water balance, mining drainage dominates, with a total capacity of 78.2 thousand m^3/d, accounting for 56.3% of the outflow. While the percentage of mining drainage in the MGWB 418 model is similar to the percentage of groundwater intake drainage in the MGWB 417 model (50.8%), it is three times higher in absolute terms (78.2 thousand m^3/d vs. 25 thousand m^3/d). The second quantitative factor on the side of groundwater outflow (38.7%) is connected with river drainage, in the amount of 53.6 thousand m^3/d, with a significant change in character on numerous sections of watercourses from draining to infiltrating. In comparison with the Kielce region, the share of exploitation of groundwater intakes in drainage is insignificant, reaching 5.0% (6.9 thousand m^3/d), which is absolutely 3.5 times less. It is the intensive large-scale mining drainage of numerous open-pit mines, extracting about 28.5 million m^3 per year (see Section 2.2), that has led to the lateral propagation of the depressurized zone significantly beyond the boundaries of the hydrostructural unit.

The situation when reservoirs and their recharge zones were treated separately (Figure 4A) changed in the second decade of the 21st century. Detailed observations of the groundwater table began to indicate its different shape in the proximity zone of both hydrostructural units, in the southwestern part of the Major Groundwater Basin no. 417 in Kielce (Figures 3 and 4B). The archival data could be re-evaluated from the borehole at the Piekoszów railroad station, accessible again after a long period of inaccessibility, in comparison with measurements from other wells in the area, which were ambiguous (see Section 2.3). Interpretation of measurements from the boreholes located in the vicinity of Zagórze and Jaworznia clearly indicates a decrease in the water table towards the boundary of the structure. In the absence of any elements that could potentially constitute drainage objects within the structure in this region (e.g., surface watercourses, wells; see Section 2.3), the only explanation is the hydrodynamic impact of drainage functioning outside the boundaries of the major structure. Such a regional drainage base occurred inthe open pit of the Miedzianka mine, located in the western part of the Gałęzice–Bolechowice–Borków syncline, situated southwest of the MGWB 417 boundary.

The dewatering of the Ostrówka deposit in the Miedzianka mine has been carried out at level VII at an ordinate of 160 m a.s.l. since June 2009. The magnitude of inflows to the mine is significant. In 2015, the average inflows were about 31,000 m^3/d [37]. Archival studies performed within the MGWB 417 indicated that there was no impact of the Miedzianka mine. It can be assumed that such a state was a result of the limited spreading of the depression cone caused by the mine drainage. As a result of the intensification of drainage (successive lowering of exploitation ordinates; see Section 2.2) and significant lapse of time of mining drainage, the zone of lowered groundwater pressure developed in the margin, reaching the limits of the Kielce syncline. As a result, groundwater filtration from the adjacent structure (MGWB 417) was triggered. It is possible that as a result of pressure difference, the flow paths, which originally were not characterized by sufficient permeability, were opened (Figure 4B). The observed arrangement of the hydrodynamic field indicates a clear impact of the Miedzianka mine on the groundwater reservoir no. 417. Although the scale of that impact is limited (decrease in the water table by single meters, flows of the order of single thousands m^3/d—Table 3), it cannot be excluded that the flows will intensify as a result of further development of the depressurized zone in the vicinity as a result of the development of exploitation and drainage of the distant mine.

Considering changing conditions, resource calculations should take into account the possibility of lateral flows between the two structures. Such a scheme was adopted for the first time in the implementation of the prognostic variant no. 2 of the described model [36], developed to reassess the resource potential of the Kielce—Białogon intake. Obtained in the simulation assuming the increase in abstractions to the reference variant (calibrated state), the predicted outflow to the neighboring structure will be slightly smaller. Such an effect will be possible of course, only on the assumption that exploitation conditions of the Miedzianka mine will not change. Any modification in the horizontal range, and especially in depth of the mine drainage, finally will probably influence the hydrodynamic field configuration in the southwestern part of the Major Groundwater Reservoir 417. The effect of impact may be delayed in time as a result of the remoteness of the mine from the boundaries of the structure and the resulting time delay in the visualization of the effects of changes.

At present, work is underway at the Holy Cross Mountains Branch in Kielce of the Polish Geological Institute (PGI) on an appendix to the hydrogeological documentation establishing operational resources of the Exploitation Region (RE) Kielce. The authors plan to use the information from the presented research in the updated model.

5. Conclusions

In further studies on water circulation in the Kielce region, an integrated approach seems to be the most appropriate, taking into account some limited hydraulic connectivity of the considered structures and hydrodynamic stresses caused by mining activity. As far as the prognostic calculations of efficiency of individual intakes or mine drainage systems can be carried out based on detailed models of separate hydrostructural units, it is advisable to take into account the interaction between them in a holistic approach to analyzing the regional water circulation. The quantity of lateral groundwater exchange between two hydrogeological structures was estimated using mathematical modeling at 3.3–3.4 thousand m^3/d (the reconstructed current state after model calibration and prognosed variant). Correct consideration of relations between structures will result in the higher reliability of prognostic calculations covering the distribution of the groundwater hydrodynamic field and water balance sheets. In the longer term, it will be important to modify the limits of both models. In the case of the Gałęzice–Bolechowice–Borków syncline (MGWB no. 418), the range of the present model reaches Piekoszow in the northeast. The northeastern boundary of the model was established based on geological indications. The model does not take into account the Lower Paleozoic low-permeability Dyminy anticline as well as the anticline of Rykoszyn completely submerging under the Permian–Mesozoic sediments. The shifted boundary of the model should include much larger parts of the extensive Piekoszów syncline to the north, especially its entire eastern part passing into the Kielce syncline. In addition, consideration should be given to the small Promnik syncline, which links with the Piekoszow syncline from the north. The southern boundary should remain the Dyminy anticline. However, in the case of the hydrogeological model of the Kielce region (MGWB no. 417), the situation seems to be more difficult. Shifting the simulated boundary towards the west and southwest would cover structures where the water table of laterally connected reservoirs would be inclined towards the main drainage object—the Miedzianka mine. The basic difficulty would be related to finding an appropriate boundary that could limit the model from the western side. In this case, and also for regional considerations, the construction of a model combining so-far separate models described above should be deliberated, with consideration of the Permian–Triassic contact zone.

Mining exploitation within the Gałęzice–Bolechowice–Borków syncline will continue. In the central region, lowering the exploitation ordinates to 160 m a.s.l. in some of the already exploited deposits is planned. As a result, the observed regional depression will expand, covering, according to model prognosis, a major part of the syncline, except for its eastern part. If the drainage is maintained in the northwestern part, at the Ostrówka deposit (ordinate of 150 m above sea level) and as well within the more peripherally located Ołowianka-1 deposit planned for exploitation, the state of hydraulic connectivity between the synclines will be maintained or even deepened.

To improve the knowledge of the hydraulic connections of the intermediate zone between the individual MGWBs, it would be necessary to expand the network of observation boreholes in the connective area. The first two were drilled in late 2016 by the Miedzianka mine. Observations will be conducted in the permeable roof parts of the Upper Triassic separated from the Middle and Lower by low-permeability sediments. At the time of preparing the model for the planned exploitation "Ołowianka 1" deposit [37], the results of the monitoring started in 2017 were not yet available.

Additional observation wells should be drilled along with the extension of observation networks around the water intake in Kielce—Białogon, intakes of the Piekoszów town as well as with the next development of the observation network around Miedzianka mine. The Lower Triassic pore aquifer should be subjected to observation.

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References

1. El Idrysy, H.; Connelly, R. Water—the Other Resource a Mine Needs to Estimate. *Procedia Eng.* **2012**, *46*, 206–212. [CrossRef]
2. Motyka, J.; Adamczyk, Z.; Juśko, K. The historical view of the water inflows to the Olkusz zinc and lead mines (SW Poland). *Przegląd Górniczy* **2016**, *72*, 49–58. (In Polish)
3. Motyka, J.; d'Obyrn, K.; Kasprzak, A.; Szymkiewicz, A. Sources of groundwater inflows into the "Czatkowice" limestone quarry in southern Poland. *Arch. Min. Sci.* **2018**, *63*, 417–424. (In Polish)
4. Hawkins, J.W.; Dunn, M. Hydrologic Characteristics of a 35-Year-Old Underground Mine Pool. *Mine Water Env.* **2007**, *26*, 150–159. [CrossRef]
5. Chunhu, Z.; Dewu, J.; Qiangmin, W.; Hao, W.; Zhixue, L.; Xiaolong, S.; Mingpei, L.; Shaofeng, W. Water inflow characteristics of coal seam mining aquifer in Yushen mining area, China. *Arab. J. Geosci.* **2021**, *14*, 278. [CrossRef]
6. Zdechlik, R.; Gołębiowski, T.; Tomecka-Suchoń, S.; Żogała, B. Application of hydrogeochemical and geophysical methods in assessment of the influence of coal-mining waste dumps on hydrogeological environment. *Geol. Bull. Pol. Geol. Inst.* **2011**, *445*, 725–735. (In Polish)
7. Zdechlik, R.; Kmiecik, E.; Haładus, A. Estimation of the impact of mining waste dump KWK "Dębieńsko" on groundwater quality. In *Selected Problems of Geological and Hydrogeological Research for Mining and Energy*; Bukowski, P., Ed.; Główny Instytut Górnictwa: Katowice, Poland, 2012; pp. 143–154. (In Polish)
8. Duda, R. The influence of drainage wells barrier on reducing the amount of major contaminants migrating from a very large mine tailings disposal site. *Arch. Environ. Prot.* **2014**, *40*, 87–99. [CrossRef]
9. Spitz, K.; Moreno, J. *A Practical Guide to Groundwater and Solute Transport Modeling*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 1996; p. 480.
10. Kresic, N. *Hydrogeology and Groundwater Modeling*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2006. [CrossRef]
11. Anderson, M.P.; Woessner, W.W.; Hunt, R.J. *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2015.
12. Zdechlik, R. A Review of Applications for Numerical Groundwater Flow Modeling. In Proceedings of the 16th International Multidisciplinary Scientific GeoConference, SGEM 2016, Albena Resort, Bulgaria, 28 June–7 July 2016; STEF92 Technology Limited: Toronto, ON, Canada, 2016; Volume 3, pp. 11–18.
13. Bukowski, P.; Haładus, A.; Zdechlik, R. The process of mine workings flooding on the example of selected hard coal mines in the Upper Silesian Coal Basin. In *Współczesne Problemy Hydrogeologii*; t.XII; Sadurski, A., Krawiec, A., Eds.; Wydawnictwo Uniwersytetu Mikołaja Kopernika: Toruń, Poland, 2005; pp. 85–90. (In Polish)
14. Haładus, A.; Zdechlik, R.; Bukowski, P. Numerical Modeling of Flooding Process in the Part of the Janina Hard Coal Mine. In *XIII Sympozjum Współczesne Problemy Hydrogeologii. Kraków-Krynica 21-23.06*; Szczepański, A., Kmiecik, E., Żurek, A., Eds.; AGH: Kraków, Poland, 2007; pp. 789–795. (In Polish)
15. Rapantova, N.; Grmela, A.; Vojtek, D.; Halir, J.; Michalek, B. Ground Water Flow Modelling Applications in Mining Hydrogeology. *Mine Water Environ.* **2007**, *26*, 264–270. [CrossRef]
16. Surinaidu, L.; Gurunadha Rao, V.V.S.; Srinivasa Rao, N.; Srinu, S. Hydrogeological and groundwater modeling studies to estimate the groundwater inflows into the coal Mines at different mine development stages using MODFLOW, Andhra Pradesh, India. *Water Resour. Ind.* **2014**, *7–8*, 49–65. [CrossRef]
17. Hu, L.; Zhang, M.; Yang, Z.; Fan, Y.; Li, J.; Wang, H.; Lubale, C. Estimating dewatering in an underground mine by using a 3D finite element model. *PLoS ONE* **2020**, *15*, e0239682. [CrossRef]
18. Li, X.L.; Chen, S.J.; Wang, S. Study on in situ stress distribution law of the deep mine taking Linyi Mining area as an example. *Adv. Mater. Sci. Eng.* **2021**, *9*, 5594181. [CrossRef]
19. Liu, S.M.; Li, X.L.; Wang, D.K.; Zhang, D. Investigations on the mechanism of the microstructural evolution of different coal ranks under liquid nitrogen cold soaking. *Energy Sources Part A Recovery Util. Environ. Eff.* **2020**, 1–17. [CrossRef]
20. Aryafar, A.; Ardejani, F.D.; Singh, R.; Shokri, B.J. Prediction of groundwater inflow and height of the seepage face in a deep open pit mine using numerical finite element model and analytical solutions. In Proceedings of the IMWA Symposium 2007: Water in Mining Environments, Cagliari, Italy, 27–31 May 2007.
21. Niedbalska, K.; Haładus, A.; Bukowski, P.; Augustyniak, I.; Kubica, J. Modelling of changes of hydrodynamic conditions in the aquatic environment of the Maczki-Bor sand pit due to the fact of planned closure of mining operations (NE part of Upper Silesian Coal Basin-Poland). In Proceedings of the International Mine Water Association Congress, Aachen, Germany, 4–11 September 2011; pp. 231–234.
22. Niedbalska, K.; Bukowski, P.; Haładus, A. Using of groundwater flow modeling to optimize the methods of liquidation of open pit mine reclaimed by post-mining wastes. In Proceedings of the 14th International Multidisciplinary Scientific Geoconference SGEM, Albena, Bulgaria, 17–26 June 2014; Geoconference on science and technologies in geology, exploration and mining; Volume II, pp. 1035–1042.
23. Brown, K.; Trott, S. Groundwater Flow Models in Open Pit Mining: Can We Do Better? *Mine Water Environ.* **2014**, *33*, 187–190. [CrossRef]

24. Zhao, L.; Ting, R.; Wang, N. Groundwater impact of open cut coal mine and an assessment methodology: A case study in NSW. *Int. J. Min. Sci. Technol.* **2017**, *27*, 861–866. [CrossRef]
25. Szczepiński, J. The Significance of Groundwater Flow Modeling Study for Simulation of Opencast Mine Dewatering, Flooding, and the Environmental Impact. *Water* **2019**, *11*, 848. [CrossRef]
26. Różkowski, K.; Zdechlik, R.; Chudzik, W. Open-Pit Mine Dewatering Based on Water Recirculation—Case Study with Numerical Modelling. *Energies* **2021**, *14*, 4576. [CrossRef]
27. MODFLOW and Related Programs. Available online: https://water.usgs.gov/ogw/modflow (accessed on 22 March 2022).
28. Diersch, H.-J. *FEFLOW Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media*; Springer: Berlin/Heidelberg, Germany, 2014; p. 996. [CrossRef]
29. Prażak, J. *The sources of drinking water for the city of Kielce past and present In Water in the City*; Ciupa, T., Suligowski, R., Eds.; Monografie Komisji Hydrologicznej PTG, Instytut Geografii Uniwersytetu Jana Kochanowskiego: Kielce, Poland, 2014; pp. 227–236. (In Polish)
30. Solon, J.; Borzyszkowski, J.; Bidłasik, M.; Richling, A.; Badora, K.; Balon, J.; Brzezińska-Wójcik, T.; Chabudziński, Ł.; Dobrowolski, R.; Grzegorczyk, I.; et al. Physico-geographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data. *Geogr. Pol.* **2018**, *91*, 143–170. [CrossRef]
31. Rzonca, B. Hydrogeologiczne właściwości przestrzeni porowej dewońskich skał węglanowych w Górach Świętokrzyskich. *Przegląd Geol.* **2005**, *53*, 5. (In Polish)
32. Rzonca, B. The hydrogeological properties of the Devonian carbonate rocks in the Holy Cross Region, Poland. *Geologia* **2006**, *32*, 3.
33. Rzonca, B.; Prażak, J. Variability of filtration parameters of carbonate Devonian rocks in the Świętokrzyskie Mountains. *Biul. Państw. Inst. Geol.* **2002**, *404*, 233–248. (In Polish)
34. Prażak, J. *Hydrogeological Documentation of the Kielce Exploitation Area (RE), including MGWB No 417 Kielce*; PIG O/Świętokrzyski w Kielcach: Kraków, Poland, 1994. (In Polish)
35. Prażak, J. Position of hydrodynamic and economic significance of Devonian groundwater reservoirs in the Holy Cross Mountains. *Prace PIG* **2012**, *198*, 1–72.
36. Różkowski, K.; Zdechlik, R.; Kaznowska-Opala, K.; Kij, M.; Różkowski, J. *Appendix No. 3 to the Hydrogeological Documentation Establishing the Exploitation Resources of the Kielce—Białogon Municipal Intake*; Fundacja Nauka i Tradycje Górnicze, z siedzibą Wydział Górnictwa i Geoinżynierii AGH w Krakowie: Kraków, Poland, 2017. (In Polish)
37. Różkowski, K.; Zdechlik, R.; Polak, K.; Kaznowska-Opala, K.; Kubiszyn, K.; Bielec, B. *Hydrogeological Documentation Specifying the Hydrogeological Conditions in Connection with the Intended Drainage in Order to Extract Minerals from the Ołowianka Devonian Limestone Deposit*; Fundacja Nauka i Tradycje Górnicze z siedzibą Wydział Górnictwa i Geoinżynierii AGH w Krakowie: Kraków, Poland, 2017. (In Polish)
38. Szuflicki, M.; Malon, A.; Tymiński, M. (Eds.) *Balance of Mineral Resources in Poland, as of December 31 2019*; PIG-PIB: Warszawa, Poland, 2020. (In Polish)
39. Prażak, J.; Janecka-Styrcz, K.; Kos, M.; Kowalczewska, G.; Machowska, K.; Młyńczak, T.; Wróblewska, E. *Indication of the Possibility of Obtaining Mine Water from the Gałęzice-Bolechowice-Borków Area for the City of Kielce, Together with the Determination of the Impact of Mining Drainage on the Resources of Municipal Groundwater Intakes in Kielce*; PIG: Kielce, Poland, 2005. (In Polish)
40. Motyka, J.; Józefko, I.; Czop, M.; Polak, K.; Wojnicka–Put, B.; Syposz–Łuczak, B.; Knap, W.; Galiniak, G. *Hydrogeological Documentation for the Deposit "Ostrówka", in Gałęzice, Province Świętokrzyskie, Specifying the Hydro-Geological Conditions in Connection with the Exploitation of the Deposit up to a Depth of 160 m above Sea Level*; Fundacja Nauka i Tradycje Górnicze z siedzibą Wydział Górnictwa i Geoinżynierii AGH w Krakowie: Kraków, Poland, 2005. (In Polish)
41. Porwisz, B.; Kowalski, J.; Koziara, T.; Knez, J.; Szklarczyk, T. *Hydrogeological Documentation of the Groundwater Exploitation Region (RE) Kielce—Update of Exploitation Resources of the Kielce—Białogon Municipal Water Intake*; Przedsiębiorstwo Geologiczne, S.A. w Krakowie: Kraków, Poland, 2003. (In Polish)
42. Białecka, K.; Kaczor-Kurzawa, D.; Janecka-Styrcz, K. *Appendix to the "Hydrogeological Documentation of the Exploitation Region (RE) Kielce, including MGWB No 417 Kielce" in Connection with the Establishment of Protective Areas of the Main GroundWater Basin No. 417 Kielce*; PIG-PIB Oddz, Świętokrzyski w Kielcach: Kielce, Poland, 2015. (In Polish)
43. Kulma, R.; Zdechlik, R. *Groundwater Flow Modeling*; Uczelniane Wydawnictwa Naukowo-Dydaktyczne AGH: Kraków, Poland, 2009. (In Polish)
44. Motyka, J.; Prażak, J.; Zapała, Z. Zonality of karst phenomena in the „Trzuskawica" quarry and its vicinity (the Świętokrzyskie Mts., Kielce region). In *Kras i Speleologia*; t. 7 (XVI); Uniwersytet Śląski: Katowice, Poland, 1993.
45. Kielce Climate. Available online: https://pl.climate-data.org/location/764743/ (accessed on 1 April 2021).
46. Różkowski, K.; Zdechlik, R.; Sikora, M.; Różkowski, J. *Appendix No. 4 to the Hydrogeological Documentation Defining the Operational Resources of the Municipal Kielce-Dyminy Water Intake*; Fundacja Nauka i Tradycje Górnicze w Krakowie: Kraków, Poland, 2020. (In Polish)